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Ant Colony Optimization for Scheduling Walking Beam Reheating Furnaces

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***Abstract*— This paper presents a new mathematical model for the walking beam reheating furnace scheduling problem (WBRFSP) in an iron and steel plant, which allows the mixed package of hot and cold slabs and aims to minimize the energy consumption and increase the product quality. An ant colony optimization (ACO) algorithm is designed to solve this model. Simulation results based on the data derived from the field data of an iron and steel plant show the effectiveness of the proposed model and algorithm.**

I. Introduction

High energy consumption and high fund occupation are two outstanding characteristics of metallurgical industry. Due to the lack of energy in the world, how to reduce energy consumption has become one core objective in the iron and steel industry. For a long time, the production scheduling problem in the iron and steel industry has attracted many researchers' attention. Indeed, many achievements have been made in the steel-making, continuous-casting and hot-rolling, solving the optimization problem with operational research and intelligent algorithms. In recent years, many people have paid their attention to integrate the production planning and scheduling systems in iron and steel enterprises, aiming to address the scheduling problem across the continuous-casting and hot-rolling processes.

The reheating furnace process is located behind the continuous-casting process and before the hot-rolling process and consumes the most energy. Generally, the production requires to optimize the scheduling of reheating furnaces, reduce the heating time of slabs, and save the energy. As the reheating furnace occupies a very important position, it has become a hot spot in research in recent years. So far, the study has mostly focused on the heat energy, such as the furnace temperature control and the slabs heating optimal control.

The walking beam reheating furnace scheduling problem (WBRFSP) was regarded as a multi-constraint knapsack problem with unlimited knapsack capacity in [1]. In [1], a genetic local search algorithm was also designed with the target of minimizing the slabs heating time. Given the close relationship between the reheating furnace and hot-rolling process, the WBRFSP was described as multi-source, multi-machine and parallel earliness/tardiness scheduling problem in [2], which was solved with a hybrid algorithm based on heuristic rules and evolutionary computation with the aim of dispatching the slabs into the hot-rolling process on time. But, neither [1] nor [2] considered the capacities of reheating furnaces. Broughton *et al.* [3] brought forward an improved genetic algorithm (GA) to solve the problem, without giving the specific model.

The WBRFSP aims to decide to which furnace each slab should be assigned for heating and the sequence of slabs in each furnace, under the condition that the sequence in which slabs should be output from the furnaces for the following hot-rolling process is given beforehand. It requires to minimize the slabs' heating time to reduce energy consumption and enhance the production quality, under the condition that each slab should satisfy the heating temperature which is given by the following hot-rolling process.

This paper establishes a new model for the WBRFSP, which considers both hot and cold slabs and aims to minimize the energy consumption. Based on this model, an ant colony optimization (ACO) algorithm is designed to solve the WBRFSP. A simulation study is conducted based on the data derived from the field data of an iron and steel plant. The experimental results validate the effectiveness of both the proposed model and algorithm for solving the WBRFSP.

II. The Reheating Furnace Shceduling Problem

A. Reheating Furnace Production Process

The hot-rolling process of slabs usually consists of three stages, i.e., furnace reheating, rough rolling and finishing rolling, where the furnace reheating stage consumes as much as half of the energy in the hot-rolling process. A furnace has the two major functions: heating the slabs to the required rolling temperature for qualified products and playing an essential role of buffer for the following hot-rolling process. The slabs which need to be heated in furnaces come from the slab storage, the soaking pit or the continuous-casting process respectively. The process flow is shown in Fig. 1.

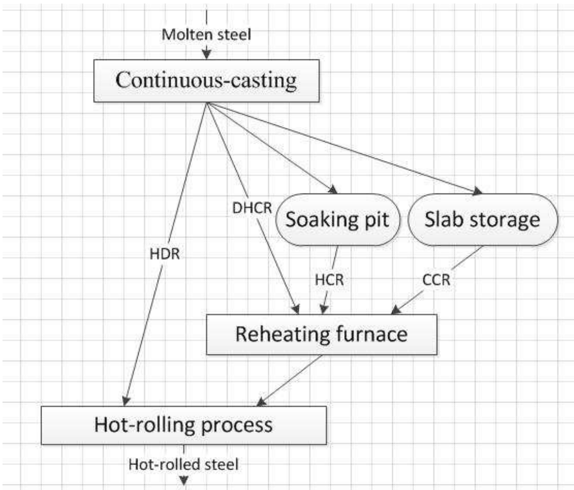

Fig. 1. Flow of slabs for the furnace reheating process.

As shown in Fig. 1, there are four alternative routes for the slabs to flow from continuous-casting to hot-rolling, which are Hot Direct Rolling (HDR), Direct Hot Charge Rolling (DHCR), Hot Charge Rolling (HCR), and Cold Charge Rolling (CCR), where only HDR does not go through the reheating furnace. The reheating furnace process is very important and useful because only when the temperature of slabs reaches a certain high level, which is usually over 1200 degree Celsius, can the slabs meet the hot-rolling working condition. Slabs following different routes will have different original temperatures before entering the reheating furnace. Since directly going down from continuous-casting, the temperature of slabs using DHCR is much higher than that of slabs using HCR, which are insulated in the soaking pit. The temperature of slabs using CCR is the lowest since their temperature almost equals the room temperature. Because of the different original temperatures, the heating time and the elevated temperature curve of slabs are also different.

In modern iron and steel enterprises, walking beam reheating furnaces are commonly used. A walking beam reheating furnace has three heating zones, i.e., the preheating zone, heating zone and soaking zone, and thus can hold multiple slabs at the same time. The temperature of a slab will reach the expected target during these three zones. Figure 2 shows the internal structure of a walking beam reheating furnace.

In the iron and steel industry, the devices are usually equipped as follows: one multi-strand casting machine or several parallel single strand casting machines; one reheating furnace group, which contains two to five furnaces with different capacities; one hot-rolling machine. The operation of a reheating furnace can be briefly described as follows. At the beginning, the slabs are fed into the furnace one by one through the entrance. If the furnace is full, the excess slabs can not enter it until some slabs inside are drawn out. In the furnace, the slabs move through the three zones to get a full and even heating. Finally, the slabs are drawn out one by one through the end of furnace when their temperatures reach the required hot-rolling goals. However, if a slab has not been drawn out, the next adjacent slab can not leave even if it has reached the temperature.

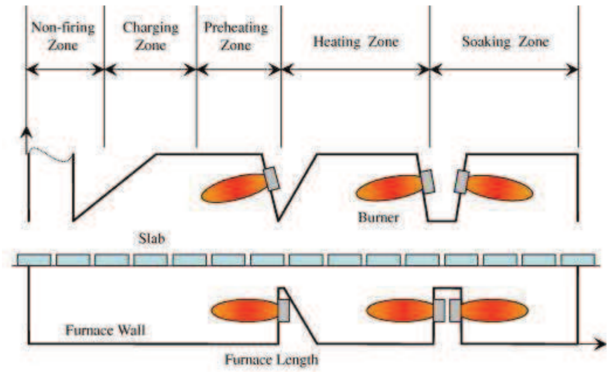

Fig. 2. Internal structure of a walking beam reheating furnace.

So, how to distribute slabs reasonably to different furnaces to minimize the heating time of slabs in furnaces under the situation that the production quality do not decline is the main objective. The technological requirements that must be considered are summarized as follows.

1) The sequence of slabs drawn out from furnaces must be strictly the same as the sequence of slabs entering the hot-rolling process, which is formulated in the rolling plan.
2) Each furnace can heat a number of slabs at the same time, but the capacity of each furnace is limited.
3) Each slab has its minimum heating time. Non-adequate heating time can not guarantee the production quality.
4) Each slab has its maximum heating time. Excess heating will bring unnecessary burning loss and lower quality.
5) A heated slab must wait inside a furnace before its time to roll.
6) In one furnace, the input slab sequence is the same as the output slab sequence.
7) The hot-rolling machine has the maximum waiting time between two adjacent slabs. Since the production power of a hot-rolling machine is huge, too much waiting time will result in too much loss. So, the waiting time should be limited when it is working.
8) The hot-rolling machine also has the minimum waiting time between two adjacent slabs due to technical requirements. So, the exit time gap between any two adjacent slabs from all furnaces must be larger than the minimum waiting time of the hot-rolling machine.
9) At one time, only one furnace can output slabs to the hot-rolling machine.

Nowadays, the scheduling method used in the iron and steel production usually distributes slabs to different furnaces in order, i.e., the first slab is sent to furnace 1, the second slab is sent to furnace 2, and so on. This method works, but with a low efficiency. To increase the efficiency, the following should be considered:

1) In one furnace, the smaller the difference of the entrance temperature between two adjacent slabs and the difference of the exit temperature between them, the better. That is, the closer the heating curves of two adjacent slabs, the better.
2) The shorter the time the hot-rolling machine waits, the better. As mentioned above, too much waiting time of the hot-rolling machine will bring too much economic loss.
3) The shorter the time the slabs need to be heated in furnaces, the better. Under the same production quality, reducing the slab heating time can cut down the economic cost.

B. Mathematical Model for the WBRFSP

According to the above description, the model for the WBRFSP can be established. The following parameters will be used in this model.

- N: The number of slabs that need to be heated
- M: The number of working furnaces
- S: The sequence of slabs $S = \{S_1, S_2, \ldots, S_N\}$, where slab S_i will be the i-th one among all slabs to enter the hot-rolling process. In other words, the sequence number of a slab in S is equal to the sequence number in which the slab will be rolled by the hot-rolling machine.
- F: The set of furnaces. $F = \{F_1, F_2, \ldots, F_M\}$
- C_k: The capacity of furnace F_k, i.e., the maximum number of slabs F_k can heat at the same time
- N_k: The number of slabs to be heated in furnace $F_k \in F$
- T_{ik}: The entrance temperature of slab S_i in furnace F_K
- T^*_{ik}: The exit temperature of slab S_i in furnace F_K
- $t_{i,start}$: The entrance time of slab S_i
- $t_{i,exit}$: The exit time of slab S_i
- $t_{ik,start}$: The entrance time of slab S_i in furnace F_K
- $t_{ik,exit}$: The exit time of slab S_i in furnace F_K
- U_{ikmin}: The minimum heating time of slab S_i in furnace F_K
- U_{ikmax}: The maximum heating time of slab S_i in furnace F_K
- q_{ik}: The minimum entrance time gap between slab S_i and its next slab in furnace F_k
- t_{hmin}: The minimum hot-rolling machine waiting time between two adjacent slabs
- t_{hmax}: The maximum hot-rolling machine waiting time between two adjacent slabs
- $a_{ik} = \begin{cases} 1, & \text{if slab } S_i \text{ is heated in furnace } F_k \\ 0, & \text{otherwise} \end{cases}$
- $o_{ijk} = \begin{cases} 1, & \text{if in furnace } F_k\text{, slab } S_j \text{ is subsequent to slab } S_i \\ 0, & \text{otherwise} \end{cases}$
- $t_{ijk} = \begin{cases} 1, & \text{if in furnace } F_k\text{, slab } S_j \text{ is the } C_k\text{th slab to be heated after slab } S_i \text{ (so } F_k \text{ is full), i.e., } \sum_{m=i}^{j}\sum_{l=m+1}^{j} o_{mlk} = C_k \\ 0, & \text{otherwise} \end{cases}$
- δ_{01}: Penalty coefficient of slab entrance temperature
- δ_{02}: Penalty coefficient of slab exit temperature
- δ_1: Penalty coefficient of hot-rolling machine waiting time
- δ_2: Penalty coefficient of slab heating time

Based on the above parameters, the model is given as:

$$min \left\{ \begin{array}{l} \delta_{01}\sum_{k=1}^{M}[\sum_{i=1}^{N_k}(\mid T_{ik} - \sum_{i\neq j} T_{jk}o_{ijk} \mid)]+ \\ \delta_{02}\sum_{k=1}^{M}[\sum_{i=1}^{N_k}(\mid T^*_{ik} - \sum_{i\neq j} T^*_{jk}o_{ijk} \mid)]+ \\ \delta_1 \sum_{i=1}^{N}(t_{i+1,exit} - t_{i,start} - t_{hmin})+ \\ \delta_2 \sum_{k=1}^{M}[\sum_{i=1}^{N_k}(t_{ik,exit} - t_{ik,start})] \end{array} \right\} \tag{1}$$

$$\sum_{k\in\{1,\ldots,M\}, i\in\{1,\ldots,N\}} a_{ik} = 1 \tag{2}$$

$$t_{ik,exit} - t_{ik,start} \geqslant \sum_{k=1}^{M} U_{ikmin}a_{ik} \tag{3}$$

$$t_{ik,exit} - t_{ik,start} \leqslant \sum_{k=1}^{M} U_{ikmax}a_{ik} \tag{4}$$

$$\begin{array}{l} t_{i+1,exit} - t_{i,exit} \geqslant t_{hmin}, \\ \quad j > i, i, j \in \{1,\ldots,N\}, k \in \{1,\ldots,M\} \end{array} \tag{5}$$

$$\begin{array}{l} t_{i+1,exit} - t_{i,exit} \leqslant t_{hmax}, \\ \quad j > i, i, j \in \{1,\ldots,N\}, k \in \{1,\ldots,M\} \end{array} \tag{6}$$

$$\begin{array}{l} t_{j,exit} > t_{i,exit}, \\ \quad j > i, i, j \in \{1,\ldots,N\}, k \in \{1,\ldots,M\} \end{array} \tag{7}$$

$$\begin{array}{l} (t_{jk,start} - t_{ik,start} - q_{ik})o_{ijk} \geqslant 0, \\ \quad j > i, i, j \in \{1,\ldots,N\}, k \in \{1,\ldots,M\} \end{array} \tag{8}$$

$$\begin{array}{l} (t_{jk,start} - t_{ik,exit})t_{ijk} \leqslant 0, \\ \quad i, j \in \{1,\ldots,N\}, k \in \{1,\ldots,M\} \end{array} \tag{9}$$

In the above model, object (1) is to minimize the economic expenses. Constraint (2) ensures that each slab will go into one and only one furnace. Constraints (3) and (4) ensure that the heating time of a slab in a furnace is longer than its minimum heating time and shorter than the maximum heating time. Constraints (5) and (6) ensure that the exit time gap of two adjacent slabs into the hot-rolling machine is larger than the hot-rolling machine's minimum waiting time but smaller than the maximum waiting time. Constraint (7) ensures that all the slabs exit furnaces in the same order as the sequence required by the hot-rolling machine. Constraint (8) ensures that two adjacent slabs in a furnace satisfy the minimum entrance time gap condition. Constraint (9) ensures that each furnace satisfies its capacity limit.

III. Proposed ACO Algorithm for the WBRFSP

In the WBRFSP, since slabs must exit furnaces in the hot-rolling sequence, and slabs in a same furnace follows the first-in-first-out rule, the task of assigning slabs into furnaces may be regarded as a knapsack problem in combinatorial optimization with the goal to minimize the energy consumption. Given that there are some relationships between two adjacent slabs in a furnace, the WBRFSP can be considered as a two-dimension expense knapsack problem, which is an NP-hard problem [4]. The larger the problem size, the harder the calculation. Due to this, we can use metaheuristic algorithms, e.g., ACO, to solve the problem. ACO simulates the action of ants and has shown to be one of most effective algorithms in solving traveling salesman problems, vehicle routing problems and scheduling problems [5, 6, 7].

This paper designes an ACO algorithm for solving the WBRFSP. According to the features of the WBRFSP, slabs and furnaces are taken as routing points in the solution construction process. An ant is first sent out from the first slab and chooses a furnace for it via the state transition rule, and then, moves to the next slab and chooses a furnace for it, and so no. The process continues until the ant reaches the last slab and chooses a furnace for it. The key components of the proposed ACO algorithm are described as follows.

A. Heuristic Information

Heuristic information η_{ik} reflects the expectation that an ant, when at slab S_i, chooses furnace F_k. To reduce the frequency of mixed hot and cool slabs and enhance the productivity of reheating furnaces and hot-rolling machine, this paper defines η_{ik} as:

$$\eta_{ik} = \frac{1}{(\varepsilon_1 h_k^{sum} + \varepsilon_2 \mid T_{ik} - T_{(i-1)k} \mid + \varepsilon_3 \mid T_{ik}^* - T_{(i-1)k}^* \mid)} \tag{10}$$

where h_k^{sum} represents the total heating time of existing slabs in furnace F_k; T_{ik} and $T_{(i-1)k}$ represent the entrance temperatures of S_i and $S_(i-1)$ in F_k; T_{ik}^* and $T_{(i-1)k}^*$ represent the corresponding exit temperatures; $\varepsilon_1, \varepsilon_2$ and ε_3 are coefficients. From Eq. (10), slab S_i can be sent to a furnace with the following characteristics:

1) The total heating time of existing slabs in the furnace should be small.
2) The entrance temperature difference and exit temperature difference between two adjacent slabs in the furnace should be small.

B. State Transition Rule

In this paper, the state transition rule is designed as follows. Initially, all pheromone trails are initialized with an equal amount of pheromone, and each ant starts from the first slab. When an ant is at slab S_i, with a probability $1 - q_0$, where $0 \leqslant q_0 \leqslant 1$ is a parameter of the decision rule, the ant chooses furnace F_k for S_i probabilistically as follows:

$$p_{ik} = \frac{(\tau_{ik})^\alpha (\eta_{ik})^\beta}{\sum_{l\in\omega_i} (\tau_{il})^\alpha (\eta_{il})^\beta}, k \in \omega_i \tag{11}$$

where α and β indicate the weight of pheromone and heuristic information respectively; τ_{ik} represents the pheromone between slab S_i and furnace F_k; w_i is the set of available furnaces for slab S_i. With the probability q_0, the ant chooses the furnace with the maximum probability, i.e., the furnace that satisfies the following formula:

$$k = \underset{g\in\omega_i}{\operatorname{argmax}}\{(\tau_{ig})^\alpha (\eta_{ig})^\beta\} \tag{12}$$

C. The Objective Function

Initially, we assume all furnaces are empty, and the initial time is set to zero. When an ant constructs a complete solution, the solution represents the assignment of furnaces to slabs. From the solution, according to Constraints (3)–(9), we can determine the entrance time and exit time of each slab in the assigned furnace, based on the pre-condition of the hot-rolling sequence of slabs. Finally, we calculate the objective value with Eq. (1). Suppose the entrance time difference between two adjacent slabs is t_{dif}, the entrance and exit times of slab S_i are calculated as follows:

- If $i = 1$, then $t_{ik,start} = 0$ and $t_{ik,exit} = U_{ikmin}$.
- If $i > 1$, but S_i is the first slab in furnace F_k, then $t_{ik,start} = i * t_{dif}$, $t_{ik,exit} = max(t_{(i-1)k,exit} + t_{hmin}, t_{1k,exit} + i * t_{dif})$.
- If $i > 1$, and the number of slabs in furnace F_k is less than its capacity, then, assuming the previous slab in F_k is S_j, we have $t_{ik,start} = t_{jk,start} + (i - j) * t_{dif}$, $t_{ik,exit} = max(t_{(i-1)k,exit} + t_{hmin}, t_{1k,exit} + i * t_{dif})$.
- If $i > 1$ and the number of slabs in furnace F_k is equal to its capacity, then, assuming slab S_j has just left F_k, we have $t_{ik,start} = t_{jk,exit}$, $t_{ik,exit} = max(t_{(i-1)k,exit} + t_{hmin}, t_{1k,exit} + i * t_{dif})$.

D. Local Search

To accelerate the convergence speed and reduce the operation time, we use a neighborhood search algorithm as the local search scheme for each ant in each iteration. The local search scheme selects stochastically two slabs which are not assigned to the same furnace to produce a critical region solution. If the critical region solution is better than the original solution, the original one is replaced; otherwise, we repeat the local search process until the maximum number of local search iterations is reached.

E. Pheromone Update Rule

The pheromone trails between slabs and furnaces are locally updated after each ant constructs a solution as follows:

$$\tau_{ik} = \begin{cases} \tau_{ik} + (f_l)^{-1}, & if\ i,k \in r_l; \\ \tau_{ik}, & else. \end{cases} \tag{13}$$

$$\tau_{ik} = min\{\tau_{max}, max\{\tau_{min}, (1-\rho)\tau_{ik}\}\} \tag{14}$$

where r_l is the solution found by the current ant; f_l is the objective value of r_l; τ_{max} and τ_{min} are the upper and lower pheromone limits respectively; $\rho \in (0, 1)$ is the evaporation rate.

After an iteration of the ACO algorithm, i.e., all ants finish constructing solutions, the pheromone trails are also updated as follows:

$$\tau_{ik} = \begin{cases} \tau_{ik} + (f_b)^{-1}, & if\ i,k \in r_b; \\ \tau_{ik}, & else. \end{cases} \tag{15}$$

$$\tau_{ik} = min\{\tau_{max}, max\{\tau_{min}, (1-\rho)\tau_{ik}\}\} \tag{16}$$

where r_b is the best solution found over all ants and f_b is the objective value of r_b.

F. Algorithm Framework

The framework of the proposed ACO algorithm for solving the WBRFSP is summarized as follows:

1) Get the information of slabs
2) Initialize the parameters, such as α, β, τ_{max}, τ_{min}, q_0, $\tau_{ik} = \tau_{min}$ and the initial heuristic information η_{ik}.
3) Set each ant out at slab S_1
4) Each ant constructs a solution according to the state transition rule. Get the best solution locally and update the pheromone with Eqs. (13) and (14).
5) After one iteration, update the pheromone according to Eqs. (15) and (16).
6) Repeat Step 3 to Step 5 till the maximum number of iterations is reached.

IV. Simulation Study

To validate the effectiveness of the proposed model and ACO algorithm, we generate some simulation data for our experiments based on field examples taken from one iron and steel plant in China and the information mentioned in [7, 8]. These data were divided into three types according to the entrance temperature to furnaces: cold slab (entrance temerature $25°C$), insulating pit's slab (entrance temerature $500°C$) and hot slab (entrance temerature $930°C$), as shown in Table I.

TABLE I

Experiment Data Type

Type	Entrance Temp.	Exit Temp.	Min. Heating Time
1	$930°C$	$1200°C$	90 min
2	$500°C$	$1200°C$	90 min
3	$25°C$	$1500°C$	160 min

In this paper, we carry out two groups of experiments. In both groups of experiments, the main parameters of the ACO algorithm were set as follows: the maximum number of iterations was set to 50; $\alpha = 1$, $\beta = 7$, $\rho = 0.1$, $\tau_{max} = 1$, $\tau_{min} = 0.01$, $q_0 = 0.8$, the iteration step-size of neighborhood search was 10. The production parameters were set as follows: Each furnace has a capacity of 30, $q_{ik} = 2$ minutes, $t_{hmin} = 2$ minutes, $t_{hmax} = 10$ minutes, and the minimum heating time U_{ikmin} was set as shown in Table I, and $U_{ikmax} = 1.5 \times U_{ikmin}$.

TABLE II

Comparison of Two Models on Homogeneous Slabs

Slab Number	Existent Model	Proposed Model		
		Best	Average	Worst
60	4183.2	4104.3	4183.2	4224.5
80	4294.8	4267.5	4294.8	4319.5
100	4405.7	4394.4	4405.7	4416.2
143	6587.9	6566.2	6587.9	6598.7

TABLE III

Comparison of Two Models on Mixed Cold and Hot Slabs

Slab Number	Existent Model	Proposed Model		
		Best	Average	Worst
60	$2715°C$	$1810°C$	$1810°C$	$1810°C$
100	$2715°C$	$1810°C$	$1810°C$	$1810°C$

In the first group of experiments, we try to validate the effectiveness of the proposed model in comparison with the existent model used in the literature for the WBRFSP based on the proposed ACO algorithm. In the existent model, the objective function is given as follows:

$$min \left\{ \begin{array}{c} \delta_1 \sum_{i=1}^{N} (t_{i+1,exit} - t_{i,start} - h_{min}) + \\ \delta_2 \sum_{k=1}^{M} [\sum_{i=1}^{N_k} (t_{ik,exit} - t_{ik,start})] \end{array} \right\}. \tag{17}$$

In the experiment, the main parameters of the ACO algorithm are as given above. The number of ants in the ACO algorithm was set to 30, and there were 3 furnaces. We run the ACO algorithm 50 times for each group of data. The results regarding the best, worst, and average solutions over 50 runs on homogeneous slabs (i.e., there are only one type of slabs involved) are shown in Table II. From Table II, it is easy to find out that the results of the two models are quite similar. So, for only one kind of slabs, both models can work well. But, how about mixed cold and hot slabs? The results for mixed cold and hot slabs are shown in Table III.

The data chosen in this paper included two kind of slabs: cold slabs and hot slabs. The entrance temperature difference bewteen these two kinds of slabs was almost 900 degrees centigrade. To avoid damaging the slabs' equity, hot

TABLE IV
BASIC RESULTS OF ACO WITH $\rho = 0.1$ ON MIXED SLABS

Slab Type	Slab Nos.	ACO			
		b sol	w sol	b t	w t
1	60	5400	5400	178	178
1	150	14400	14400	418	418
3	60	9600	9600	278	278
1,2	60	5486	5486	178	178
2,1	60	5486	5486	178	178
1,3	60	8488	8602	224	220
1,3	300	37790	38290	1010	978
1,2,3	60	7480	8230	208	208
1,2,3	300	35019	37448	748	805

TABLE V
RESULTS OF ACO WITH DIFFERENT EVAPORATION RATES

Slab Type	Slab Nos.	ACO, $\rho = 0.3$				ACO, $\rho = 0.4$			
		b sol	w sol	b t	w t	b sol	w sol	b t	w t
1,3	60	8488	8488	224	224	8488	8488	224	224
1,3	300	37790	37790	1010	1010	37790	37790	1010	1010
1,2,3	60	7460	7480	208	208	7480	8340	208	243
1,2,3	300	35019	36065	748	771	35019	37236	748	790

slabs and cold slabs should be heated separately if possible. The information shown in Table III were the summation of the entrance temperature difference and exit temperature difference of slabs. From Tables II and III, the effectiveness of the model designed in this paper is validated, especially for mixed slabs heating problem. The simulation data were derived in this paper, which is much less complicated than the data in the real world. If we use real-world data, the advantage of the new model would be much larger.

The second group of experiments aims to investigate the effect of one key parameter, i.e., the pheromone evaporation rate ρ, on the performance of the proposed ACO algorithm. The main parameters of the ACO algorithm were set the same as given above. The number of ants was set to 50, and the number of furnaces was 4. There are three types of slabs, as shown in Table III. The results regarding the basic results with $\rho = 0.1$ and different values of ρ are shown in Tables IV and V, respectively. In these two tables, "b sol" and "w sol" mean the best and worst solutions resepctively, while "b t" and "w t" are the total heating time of all slabs in the best and worst solutions resepctively. When there were more than one type of slabs heating, this paper assumed that the number of each type was equal.

From Tables IV and V, it can be seen that the performance of the ACO algorithm is sensitive to the value of the evaporation rate. When the evaporation rate is increased from 0.1 to 0.3, the algorithm's performance is improved. This is because increasing the evaporation rate enhances the ACO algorithm's ability of escaping from local optima. However, the algorithm becomes divergent while the evaporation rate is further increased to 0.4.

V. CONCLUSIONS

The walking beam reheating furnace scheduling problem (WBRFSP) is an important production scheduling problem in iron and steel enterprises. Considered the mixed packing of hot and cold slabs, this paper proposes a new mathematical model for the WBRFSP, which aims to minimize the heating time, the hot-rolling machine waiting time and the entrance and exit temperature differences between two adjacent slabs to furnaces. Based on the model, the paper designs an ACO algorithm to solve the WBRFSP. A simulation study was conducted, which validated the effectiveness of the proposed WBRFSP model in comparison with the existent model in the literature and the effectiveness of the proosed ACO algorithm in solving the WBRFSP. The experimental results also showed that even though the ACO algorithm has a problem of being tracked to local optima, properly increasing the evaporation rate of pheromone trails may help the algorithm to avoid this problem.

In the future, we will further improve the proposed ACO algorithm for solving the WBRFSP and develop other algorithms, e.g., GAs, to solve the problem and compare their performance.

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